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REVIEW

Review of Path-following Control Systems for Maritime Autonomous Surface Ships

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Abstract

A review presents the state-of-the-art path-following control systems for maritime autonomous surface ships, where the special focus is placed on the guidance subsystem and control subsystem. The path following control system is one of the basic requirements for autonomous ships since it guarantees that the ship can track the predefined path with small cross-track errors. The path following problem is firstly defined, and the cross-track error dynamics are derived from the kinematic equations of marine surface ships. The classical guidance laws are introduced, and the governing equations are also presented in this paper. A review of the guidance laws and controllers for the maritime autonomous surface ships has been carried out based on relevant journal and conference papers. Several important properties and characteristics, such as control structure, guidance law, control method, stability, environmental disturbance and vessel dynamics, are defined for the comparative analysis. Finally, the summary and a discussion on the most used technologies for the path following control of marine autonomous surface ships are presented and highlighted.

Keywords Maritime autonomous surface ship; Path following; Guidance law; Control method; Stability

1 Introduction

Maritime accidents usually cause a large loss of human lives, in addition to material losses and damage to the environment. As reported in the safety and shipping review (Allianz Global Corporate and Speciality, 2018), more than 75% of maritime accidents are caused by human errors. It is expected that marine autonomous ships will reduce the number of accidents, by removing human failures. In addition, increasing the automation in ships will require fewer onboard seafarers, which is a potential solution for the shortage of workers in the maritime industry in the near future. Meanwhile, as reported in Markets&Markets (2021), the global autonomous ships market size is projected to reach 14.2 billion dollars by 2030 with a 9.3% growth rate from 2020 to 2030.

Recent years have seen the rapid development of autonomous ship concepts. To illustrate the situation, Rolls-Royce (2015) led a 6.6 million dollar project that brought together universities, ship designers and shipyards to make autonomous ships a reality. It paved the way for autonomous ships. In 2016, Norway opened the World's first official test bed, the Trondheim fjord test bed, for autonomous ships (Maritime, 2016). In 2019, the Minister of the Sea of Portugal presented the first edition of the Bluetech Accelerator Ports & Shipping 4.0, in which, smart shipping and autonomous ships are recognized as the major trends. In 2021, the Maritime Safety Committee of IMO has completed the analysis of relevant ship safety conventions, and the next steps for regulating Maritime Autonomous Surface Ships (MASS) will be assessed (IMO). Recently, the autonomous ship prototype, Yara Birkeland, carried out autonomous shipping tests in Norway.

One of the basic requirements for the marine autonomous surface ship is to follow the predefined path with small cross-track errors. This property is well known as the path following control system, which mainly consists of the guidance subsystem, navigation subsystem and control subsystem. This paper focuses on the state-of-the-art of path following control systems in the published papers, more precisely the guidance and control system, for marine autonomous surface ships. To the authors' best knowledge,

Article Highlights

- The state-of-the-art path-following control systems for maritime autonomous surface ships are summarised.
- The classical controller and guidance laws as well as the governing equations are presented.
- Several important properties and characteristics are defined for the comparative analysis.

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few papers give an exhaustive review of the guidance laws and control methodology used for the path following control of marine autonomous surface ships. Therefore, it is urgent and necessary to investigate the path following the control system of marine autonomous surface ships and present the statistical distribution of the current guidance technologies and control methodologies used in the published papers.

This paper is organized as follows: section 2 introduces the path following the control problem, where the error dynamics are presented with the kinematics of marine surface ships. In section 3, the classical guidance laws are firstly introduced and the state-of-the-art of path following control of marine surface ships is reviewed, as well as the control methodologies. At last, a comparative study is carried out using the defined properties and characteristics based on the selected papers. The conclusions are given in section 4.

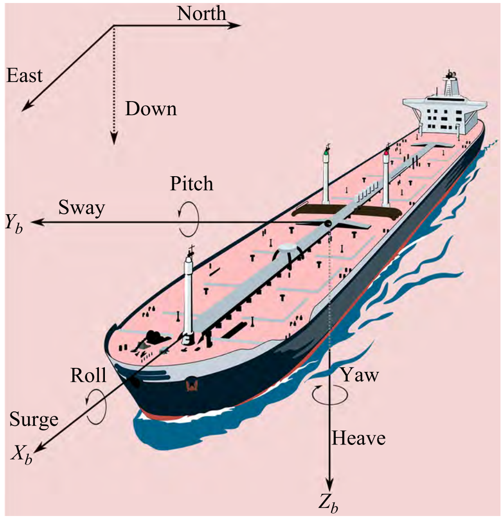

Figure 1 The motions of marine surface ships in waves (Fossen, 2011)

2 Path following control problem

The motions of the marine surface ships in waves are usually described in 6 degrees of freedom (DOFs), as presented in Figure 1. They are the surge, sway, and yaw motions, which are described in the horizontal plane, and roll, pitch and heave motion, which is described in the vertical plane. For the path following control of marine surface ships, the surge, sway and yaw motions or well known as manoeuvring motions, are typically considered, where the hydrodynamic coefficients usually can be approximated using constant values (Faltinsen, 1993). Sometimes roll motion is also augmented to the manoeuvring motions considering its coupling effect on yaw and sway motion (Fossen, 2011; Sutulo and Guedes Soares, 2011).

A typical autonomous path following system usually consists of the three basic subsystems, guidance, navigation, and control system, which are also well known as the GNC system, as presented in Figure 2. The main goal of the GNC system is to control the movement of autonomous ships according to the specified task commands. The task of the navigation system is to determine the state vectors, including the location and orientation, of the autonomous ships from the onboard sensors. The guidance system generated the control command according to the ship's state vectors at a given time and the requirement of the task. The control system will execute the guidance commands by manipulating the thruster forces and rudder, to achieve the task.

2.1 Cross-track error of path following control

The path following control problem of maritime autonomous surface ships is defined by assuming that the predefined path is described by a curved line in the three-dimensional space, $\boldsymbol{p}_d(\theta) = [x_d(\theta), y_d(\theta), z_d(\theta)]^{\mathrm{T}}$ and having the control objective to design a control law for the ships that ensures convergence of the ship's position $\boldsymbol{p}(t) = [x(t), y(t), z(t)]^{\mathrm{T}}$ to the path $\boldsymbol{p}_d(\theta)$.

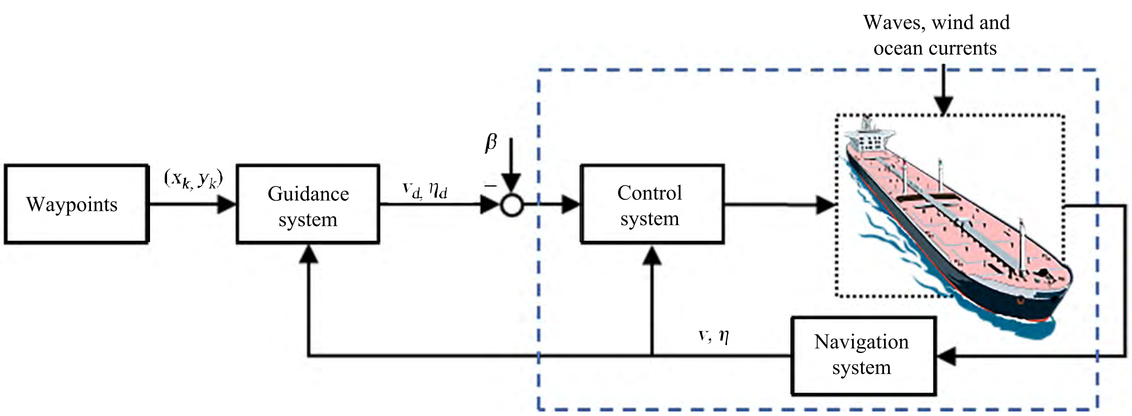

Figure 2 The guidance, navigation, and control system (GNC) for maritime autonomous surface ships (MASS) (Fossen, 2011)

For typical marine surface ships, it is usually assumed that a marine vessel is assigned to follow a two-dimensional parametrized curved path, as presented in Figure 3. Without loss of generality, the curved path is employed for the demonstration of the cross-track error of the path following control, since the straight-line path can be considered as the path with a constant path tangential angle, γ_p. As presented in Figure 3, a curved path is predefined as $\left(x_p(\theta), y_p(\theta)\right)$, where θ is a variable, and it is assumed to connect the way-points (x_j, y_j) for $j = 1, \cdots N$.

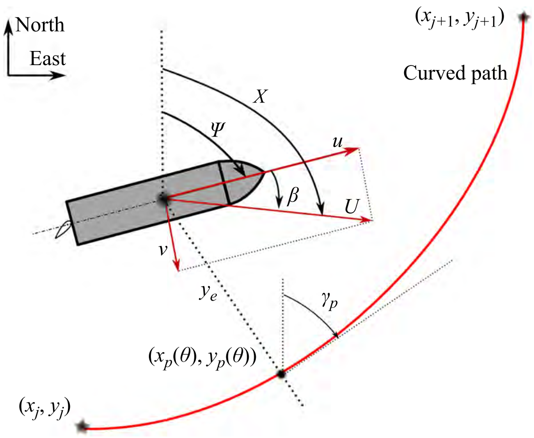

Figure 3 Path following control of autonomous ships

To analyse the motion of the ship in the horizontal plane, three geographic reference frames need to be defined first. The north-east-down (NED) coordinate system $\{n\} = (x_n, y_n, z_n)$ with the origin point, o_n, is defined as the tangent plane on the surface of the earth (Fossen, 2011). The x-axis points toward to true north, the y-axis points toward the east and the z-axis points downwards. The body-fixed coordinate system $\{b\} = (x_b, y_b, z_b)$ with the origin point, o_n, is located on the ship and usually coincides with the centre point of the ship. It is moving with the ship and satisfies the right-hand rule, where the x-axis points towards the ship's bow, as described in Figure 3. The last reference frame that needs to be defined is the path-tangential reference frame $\{p\} = (x_p, y_p, z_p)$, which is located on the predefined path, and it is rotated by an angle $\gamma_p(\theta)$ from the north-east-down (NED) reference frame using the rotation matrix (Fossen and Lekkas, 2015):

$$\boldsymbol{R}\left(\gamma_p(\theta)\right) = \begin{bmatrix} \cos\left(\gamma_p(\theta)\right) & -\sin\left(\gamma_p(\theta)\right) \\ \sin\left(\gamma_p(\theta)\right) & \cos\left(\gamma_p(\theta)\right) \end{bmatrix} \in SO(2) \quad (1)$$

where the path tangential angle is given as, $\gamma_p(\theta) = \text{atan2}(x'_p(\theta), y'_p(\theta))$.

Then, the distance from the ship location (x,y) to the predefined path can be calculated:

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix} = \boldsymbol{R}\left(\gamma_p(\theta)\right)\begin{bmatrix} x - x_p(\theta) \\ y - y_p(\theta) \end{bmatrix} \quad (2)$$

where, the y_e is the cross-track error and the x_e is the qa-long-track error equals zero by choosing the origin o_p of the path-tangential reference frame to coincide with the vertical projection point of the ship on the path $(x_p(\theta), y_p(\theta))$.

By expanding equation (2), the cross-track error y_e is defined as:

$$y_e = -\left(x - x_p(\theta)\right)\sin\left(\gamma_p(\theta)\right) + \left(y - y_p(\theta)\right)\cos\left(\gamma_p(\theta)\right) \quad (3)$$

Finally, the control objective for the path-following of marine surface ships is defined as:

$$\lim_{t \to \infty} y_e(t) = 0 \quad (4)$$

2.2 Kinematic equations of path following control

Marine surface ships moving in the horizontal plane, as described in Figure 3, are considered rigid bodies, and the kinematic equations are given as:

$$\begin{aligned} \dot{x} &= u\cos(\psi) - v\sin(\psi) \\ \dot{y} &= u\sin(\psi) + v\cos(\psi) \\ \dot{\psi} &= r \end{aligned} \quad (5)$$

where, the surge and sway velocity are defined as u and v, respectively. The ψ,r are the yaw (heading) angle and yaw rate, which can be measured using an inertial measurement unit (IMU).

Taking the derivative of Eq. (3) with respect to time and substituting (5) into the results, gives:

$$\dot{y}_e = U\sin\left(\psi - \gamma_p(\theta) + \beta\right) \quad (6)$$

where, the ground speed of the ship, U, is defined as $U = \sqrt{u^2 + v^2}$. The phase angle, β = atan2 (v, u) is the drift angle, and it is the difference in heading angle ψ and course angle χ.

$$\chi = \psi + \beta \quad (7)$$

The dynamic equation of the cross-track error, y_e , can be further simplified as:

$$\dot{y}_e = U\sin\left(\chi - \gamma_p(\theta)\right) \quad (8)$$

3 Path following control in autonomous ships

In this section, the path following control state of art for maritime autonomous surface ships is reviewed. The guidance laws and control methods, which are widely used for the path-following control of marine surface ships are described in this section.

3.1 Guidance system

The guidance system can be considered as the command generator for the path following control of autonomous ships. As described in Figure 2, the input of the guidance system is the predefined path and real-time position and state of the ship. The output is the desired speed and heading angle for the marine surface ships. To achieve the control objective, the guidance law must ensure that the cross-track error will converge to zero in finite time by steering the rudder and rpm of the propeller, as indicated in Eq (4). As it is well known that the sway dynamics of the marine surface ship are underactuated, therefore, the guidance laws need to be designed considering the underactuated sway dynamic.

The most widely used guidance laws for path following control are usually described as geometric techniques, such as line of sight (LOS) guidance law, pure pursuit (PP), and constant bearing (CB). The line of sight guidance law gives the desired heading angle by imitating an experienced captain steering the ship towards the desired point, which is the virtual target point (VTP) located on the path. It is classified as a three-point geometric method since it involves the position of the ship, the reference point and the virtual target point (Fossen, 2011). The pure pursuit guidance law is a simple method and it only involves two points, the position of the ship and the target. The constant bearing is also a two-point guidance scheme, where the target velocity is considered.

3.1.1 Line of sight guidance law

3.1.1.1 Classical LOS

In the path following control of marine surface ships, the LOS guidance law and its modified version are most widely used considering the simple structure and easy implementation in the ship control systems (Fossen et al., 2003; Moreira et al. 2007). In Figure 4, the classical LOS and look ahead based LOS are presented. For the classical LOS guidance law, the LOS vector needs to be defined first, and usually equal to the nL_{pp} ahead of the ship. As indicated in Figure 4(a), the LOS vector is the vector from the ship position to the virtual target point on the predefined path. Thus, the desired heading angle can be calculated:

$$\begin{gathered}\psi_d(t) = \operatorname{atan2}\left(y_{los} - y(t), x_{los} - x(t)\right) \\ \left(y_{los} - y(t)\right)^2 + \left(x_{los} - x(t)\right)^2 = \left(nL_{pp}\right)^2\end{gathered} \tag{9}$$

Fossen et al., (2003) employed the nonlinear controller for the path following control of a marine craft, and the underactuated control problem was considered, where only two controls were used for the 3 DOF motions of the marine surface craft. The control laws for surge and yaw motion were derived using the backstepping control

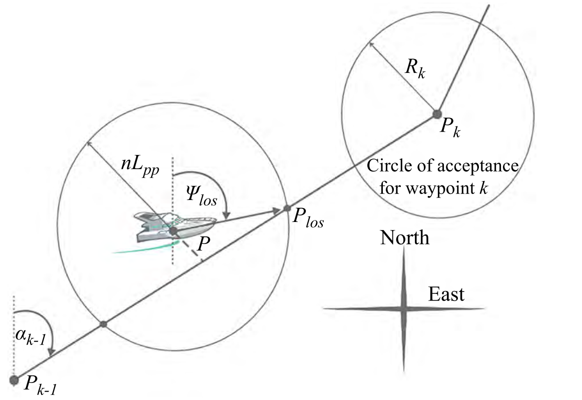

Figure 4 The classical line-of-sight guidance law (Fossen et al., 2003)

technology and the equilibrium point was proven to be uniformly globally asymptotically stable (UGAS) using the Lyapunov method. The experimental ship model test was carried out for validation.

Fredriksen and Pettersen (2006) studied the way-point manoeuvring of marine surface ships using only two control inputs in surge and yaw motion. The LOS guidance law was used for generating the heading commands. The globally κ exponentially stability of the control law was proved using cascaded control theory, and experimental results using the ship model were presented to validate the proposed control law.

Mu et al., (2018) proposed a fuzzy-based adaptive LOS guidance law for the path-following control of unmanned surface vehicles, where the backstepping control technology and neural networks were used for the control design. The closed-loop control system was proven to be uniformly ultimately bounded using the Lyapunov stability theory.

An adaptive LOS guidance law and fuzzy heading control were used (Niu et al., 2019), for the waypoints-based path following control of unmanned surface vehicles. The experimental tests were carried out to testify to the effectiveness of the proposed control system.

3.1.1.2 Look ahead LOS

A modified version of LOS, look ahead based LOS (Fossen, 2011; Fossen et al., 2015), was proposed for the calculation of the LOS vector, where the look-ahead distance needs to be defined, as described in Figure 5. The heading command is calculated using

$$\psi_d(t) = -\tan^{-1}\left(\frac{y_e}{\Delta}\right), \quad \Delta > 0 \tag{10}$$

Moreira et al., (2007) proposed a dynamic look-ahead LOS guidance for the path following control of autonomous marine surface ships. A new method was proposed for the calculation of the LOS vector to improve the convergence. The proposed method was implemented in the model of the "Esso Osaka" tank and simulations were presented for showing the effectiveness of the proposed

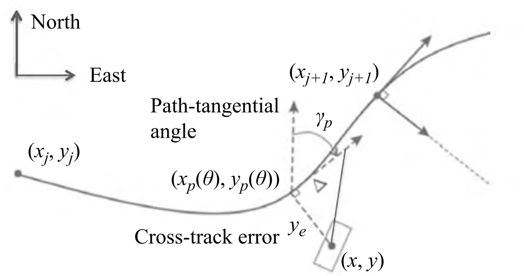

Figure 5 The look-ahead based LOS guidance law (Fossen and Lekkas, 2015)

system. A similar study was later performed by (Lekkas and Fossen, 2012), where a time-varying equation was used for the look-ahead distance calculation for the LOS guidance law. A nonlinear sliding mode controller was designed to control the yaw motion and the coupled guidance and control system was proved to be globally κ-exponentially stable. Simulation tests were carried out for the validation of the proposed guidance law.

Fossen and Pettersen, (2014) provide a uniform semi-global exponential stability (USGES) proof for the path following control of underactuated marine surface ships using the proportional LOS guidance law. The author extends the previous results, which only guarantee the global κ exponential stability, by using the cascaded stability theory. Though the USGES is slightly weaker than global exponential stability, it is still important for the autonomous system, since it guarantees the robustness of the autonomous system in the presentence of environmental disturbance.

Liu et al. (2017, 2016a) presented an extended state observer (ESO) based LOS guidance law for the path following control of marine surface ships, where a reduced-order ESO was employed to compensate for the sideslip angle due to environmental disturbance. Both simulation and experimental tests were presented in this paper. Further work can be found in (Liu et al., 2016b).

Oh and Sun (2010) used a model predictive control (MPC) for the way-point tracking control of an underactuated marine surface ship, where the input constraints were considered. LOS guidance law was incorporated into the MPC design, and the performance was improved.

Liu et al. (2018) used a model predictive control method and LOS guidance law for the path following control of ASVs, where the nonlinear Nomoto model with disturbances was employed for the control design. Simulations were carried out to show the effectiveness of the proposed method.

Moe et al., (2016a) proposed a guidance and control system for the path following control of autonomous surface vessels using absolute velocity measurements. The proposed system does not need to measure the relative velocities using expensive sensors. The cross-track error dynamics of the closed-loop were proved to be UGAS and USGES, and the results were also verified using the simulations. Further work can be found in (Moe and Pettersen, 2017).

Fossen, (2022) presented the course autopilot design for the path following and an extended Kalman filter (EKF) was used to estimate the course over ground (COG) and speed over ground (SOG) efficiently from global navigation satellite systems. The path following tests using LOS guidance law was carried out using a high-fidelity model of a MARINER class cargo ship.

3.1.1.3 Integral LOS

To handle the drift angle due to environmental disturbance, another well-known version of LOS, integral LOS(Børhaug et al., 2011, 2008; Lekkas and Fossen, 2014), was proposed by extending the classical LOS guidance with integral action:

$$\begin{aligned} \psi_d(t) &= -\tan^{-1}\left(\frac{y_e + \sigma y_{\text{int}}}{\Delta}\right), \quad \Delta > 0 \\ \dot{y}_{\text{int}} &= \frac{\Delta y}{(y_e + \sigma y_{\text{int}})^2 + \Delta^2} \end{aligned} \tag{11}$$

where, σ is a positive design parameter, and it is an integral gain.

Wan et al. (2020), designed the look-ahead distance as a function of the USV's cruising speed and the cross-tracking error for the integral LOS guidance law.

The global asymptotic stability of the proposed control system was proved, and the simulations were carried out to demonstrate its effectiveness.

An integral LOS guidance law was proposed by (Caharija et al., 2012), for the path following control of marine surface vessels, where the integral action was used to compensate for the slow varying drift angle due to the environmental disturbance. The closed-loop uniform local exponential stability was proved, and simulations were carried out to support the theoretical results. The theoretical aspects of the integral LOS guidance law can also be found in (Caharija et al., 2014). An extensive analysis of the integral line-of-sight (ILOS) guidance law for path-following control of autonomous surface vessels and underwater vessels were presented, and both simulation and experiments were used to validate the effectiveness of the proposed system (Caharija et al., 2016).

Fossen et al. (2015), proposed a nonlinear adaptive controller for the path following control of underactuated marine ships by compensating the drift forces due to the environmental disturbance, such as wind, waves and currents. The results were also extended for the path following Dubin's path. The equilibrium points of the proposed system were proven to be USGES, and the simulations show that the cross-track error and the estimated sideslip angle converge exponentially.

A direct and an indirect nonlinear adaptive controller was proposed by Fossen and Lekkas (2015), for the path following control of marine surface ships using LOS guidance law. In this paper, they proposed a disturbance observer to compensate for the drift forces due to ocean currents and proved that the proposed method is globally κ exponentially stable. The simulations for the path following control of marine surface vessels were carried out and the case for autonomous underwater vehicles was also validated.

Wiig et al. (2015) presented the uniform semi-global exponential stability proof of the integral LOS guidance law for path following control of underactuated marine vessels. Both the kinematics and dynamics of the system were taken into account, and the simulation results were presented to support the theoretical analysis.

Su et al. (2021) proposed an adaptive integral LOS guidance law for the path following control of unmanned surface vehicles with uncertainties. Three adaptive variables were constructed to eliminate the cross-track errors. The designed guidance subsystem is proved to be uniformly and ultimately bounded by the Lyapunov method.

3.1.1.4 Other works

To avoid collision with the obstacles, Moe and Pettersen, (2016) proposed set-based LOS guidance law for the path following and collision avoidance of autonomous surface vessels. The proposed guidance laws were designed to assure collision avoidance while abiding by the International Regulations for Preventing Collisions at Sea (COLREGs).

Yu et al. (2018) proposed a finite-time predictor LOS guidance law and adaptive neural network controller for the path following of unmanned surface vessels. In this paper, the author presented the theoretical analysis of the proposed system, and semi-globally uniformly ultimately bounded was proven by using the Lyapunov method. Rout et al., 2020) also used the adaptive neural network (NN) controller for the path following control of underactuated marine vehicles, where the barrier Lyapunov function (BLF) was used to deal with the system constraints and disturbance. The uniform ultimate boundedness of the closed-loop system was proved and both simulation and experimental tests were carried out for validation.

Miao et al. (2017) used the reduced-order linear extended state observer (LESOs) method to estimate the unknown sideslip angle. A filtered extended state observer (FESO) was used to estimate the time-varying sideslip angle(Li et al., 2021a, 2019), where an adaptive fuzzy controller was used for the heading control of the unmanned surface vehicles. A network-based path-tracking control of an underactuated unmanned surface vehicle was proposed by (Wu et al., 2021), and an extended state observer (ESO) was employed to estimate the unknown disturbances due to the model uncertainties and environmental disturbances. Jiang et al., (2020), used the extended state observer (ESO) to estimate unknown relative velocities together with the ocean currents in real-time.

Wang et al. (2019a) proposed a novel nonlinear adaptive path following controller for the path following of amphibious hovercrafts, where a bounded-gain-forgetting (BGF) adaptive estimator was used to compensate for the drift forces due to the environmental disturbance. A high-gain observer-based line-of-sight guidance law can be found in (Wang et al., 2019d)

Wang et al., (2019b) proposed a fuzzy observer-based adaptive path following control for an underactuated surface vehicle (USV). The control laws ensure that the proposed system was globally asymptotically stable. Simulation tests were carried out using the proposed method. Similar works can be found in(Wang et al., 2017, 2016).

Right now, the LOS guidance law has been thoroughly studied and well developed, as discussed above. Many revised versions are proposed to overcome the drawbacks of the classical LOS, for instance, the adaptive LOS, Proportional LOS, and integral LOS. The main objective of LOS guidance law is to provide the desired heading/course angle for the autonomous ships according to the geometry of positions, therefore, it did not account for other information, such as obstacles, collision rules and shipping tasks. In the future, for instance, the LOS guidance law can be extended by considering collision avoidance and COLREGs, as discussed in Moe and Pettersen, (2016), however, the stability proof of the whole guidance and control system is a challenging problem. Beside the above works, Gu et al., (2022a, 2022b) gave a comprehensive summary of LOS guidance law, disturbance observers and extended state observers for path following of both surface and underwater vehicles.

3.1.2 Pure pursuit guidance law

The pure pursuit (PP) guidance law was typically used for air-to-surface missiles and UAVs (Yamasaki et al., 2009), where the chased targets are usually static or with slow speed. As illustrated in Figure 6, the PP guidance law is the two-point guidance scheme, where only the own ship and the target are considered. In the waypoints following control, the waypoint is usually chosen as the target. The ship aligns the forward speed, $\boldsymbol{v}_a^n$, along the vector between the ship and the waypoint by choosing the desired velocity as (Breivik and Fossen, 2009):

$$\boldsymbol{v}_d^n = -\kappa \frac{\boldsymbol{p}^n}{\| \boldsymbol{p}^n \|} \tag{12}$$

where the κ is the positive constant. As can be observed, the PP guidance law will control ship travel towards the waypoints by neglecting the cross-track error, y_e. The advantage is that the resulted trajectory is short compared with the LOS guidance law. Papoulias (1993) presented a theoretical analysis of the nonlinear dynamic phenomena when using the pure pursuit guidance for marine vehicles. Xu and Guedes Soares (2018, 2015) proposed an optimized energy-efficient path-following method by combing the PP and LOS guidance law for autonomous ships. A global optimization algorithm was used to search the regularization factors, which play the trade-off between the total cross-track errors and total control energy.

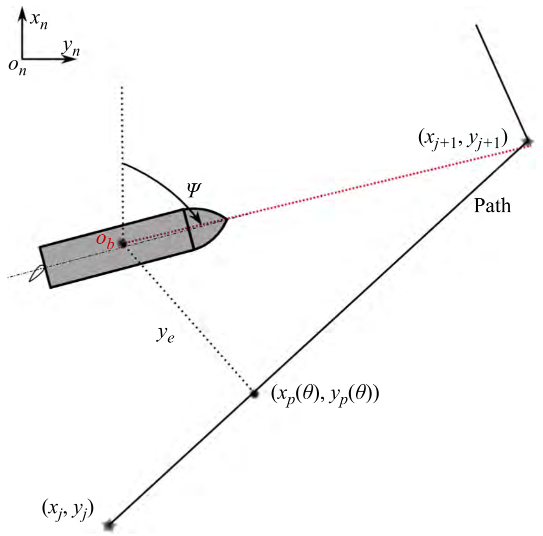

Figure 6 The pure pursuit guidance law for waypoints-based path following

3.1.3 Constant bearing guidance law

The constant bearing (CB) guidance law is also a two-point guidance method (Fossen, 2011). The geometry of CB guidance law for tracking a moving ship is presented in Figure 7. It can be assumed to be an extended version of PP guidance law by considering the velocity of the target, $\boldsymbol{v}_a^n$. CB guidance law is typically used for air-to-air missiles. Meanwhile, it was also used for collision avoidance at sea for marine vessels, where the own ship needs to steer away from a situation where another ship approaches at a constant bearing. The desired velocity is calculated using the following equation,

$$\begin{aligned} \boldsymbol{v}_d^n &= \boldsymbol{v}_t^n + \boldsymbol{v}_a^n \\ \boldsymbol{v}_a^n &= -\kappa \frac{\boldsymbol{p}^n}{\| \boldsymbol{p}^n \|} \end{aligned} \tag{13}$$

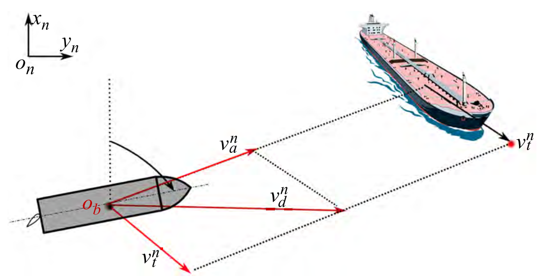

Figure 7 The Constant bearing guidance law

3.1.4 Vector field guidance law

The vector field (VF) guidance law is widely used for the path following control of unmanned aerial vehicles (UAVs) (Cho et al., 2015; Lim et al., 2014;Nelson et al., 2007, 2006; Yamasaki et al., 2009; Yanushevsky, 2011). Unlike the guidance law mentioned above, the virtual target point (or LOS vector point) does not need to be defined in the vector field guidance law. The main idea behind VF guidance law is to generate vectors around the predefined path using the mathematical equation, as illustrated in Figure 8. In this Figure, the vectors indicate the desired heading angle of a ship in the position of the arrow. When the ship tracks each vector, it will converge to the desired path eventually.

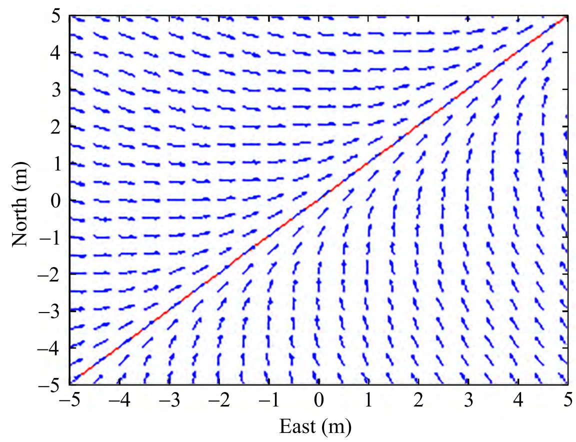

Figure 8 Vectors around the path

Nelson et al., (2007, 2006) developed the vector field guidance law for the path following control of air vehicles, where desired course angles are generated using the predefined function, as given follows:

$$\chi_d = \chi_p - \chi^{\infty} \frac{2}{\pi} \tan^{-1}(K_p y_e^p) \tag{14}$$

where, the χ_p is the path tangent angle, K_p influences the rate of the transition from χ^{∞} to zero. Inspired by the above application, Xu and Guedes Soares, (2016a) proposed the vector field guidance law for the path following control of underactuated marine surface ships. To improve the robust and converge rate, the transition region was defined along the predefined path. The vector field guidance law was defined as:

$$\chi_d = \begin{cases} \chi_p - \rho \chi^e, & \text{where } |y_e| > \tau \\ \chi_p - \rho \left(\frac{|y_e|}{\tau} \right)^k \chi^e, & \text{where } |y_e| \leqslant \tau \end{cases} \tag{15}$$

where the τ is the distance between the path and the edge of the transition region. χ^e is the entering angle, which defined the desired course angle of the ship entering the transition region. The Lyapunov method was used to prove that the proposed guidance law is global asymptotic stable. Further work and extended versions of the vector field guidance law can also be found in Xu and Guedes

Soares (2020, 2018, 2016b, 2015).

Caharija et al. (2015) carried out a comparative study for the two popular guidance laws for straight-line path-following purposes of underactuated large AUV vehicles: the integral LOS and the vector field guidance law proposed by Nelson et al. (2007, 2006). The results show that both guidance laws have a good path following control performance, with the VF guidance law performing slightly better. However, the significant chattering of the horizontal rudders can be observed, while the ILOS gives a smooth servo command.

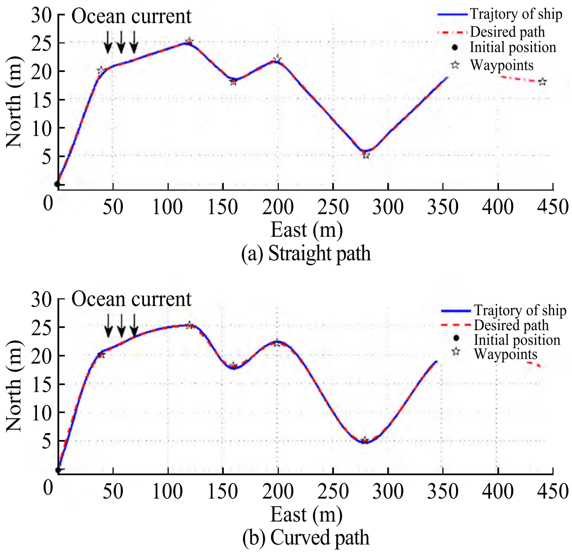

Figure 9 Path following control using the time-varying vector field guidance law (Xu et al., 2020a)

To obtain a strong stability property, Xu et al., (2020a) proposed a time-varying vector field guidance law for both straight path and curved path following control of underactuated marine surface ships. The guidance law is defined as:

$$\chi_d = \gamma_p - \operatorname{sgn}(y_e)\tan^{-1}\left(\left(\frac{|y_e|}{\Delta}\right)^{\theta(t,y_e)}\right) \tag{16}$$

where, the $\theta(t, y_e)$ is a time-varying function, which controls the converge rate and $\Delta > 0$ is a pre-defined constant. The equilibrium point of the guidance and control system is uniform semi-global exponential stable (USGES) using the Lyapunov method and cascaded system theory. The simulation results can be found in Figure 9. Further work can be found in(Hinostroza et al., 2021, 2019; Xu et al., 2021a, 2021b).

From the above discussion, the VF guidance law is more flexible, since only the mathematical equation for generating vectors needs to be defined without considering the physical definition of each parameter. However, LOS guidance laws are geometric techniques, and their parameters have a physical definition. For instance, The VF guidance law can be easily extended for collision avoidance by adding one repelling vector field around the obstacles, as discussed in (Xu et al., 2021a).

3.2 Motion control system

The motion control system for marine vessels is an active research field. Many pioneering works and papers have been published in conferences and journals. Roberts, (2008) provide a review of the early developments of marine control systems and discussed the key developments in ship autopilot design. The classical control methods are usually designed based on the knowledge of the plant model, for example, Nomoto model (Nomoto et al., 1957; Xu et al., 2020b), Abkowitz models (Abkowitz, 1980; Xu et al., 2018), just to name a few. Recently, model-free data-driven control methodologies were used for the motion control system of marine ships. Its application in the dynamic positioning of marine ships can be found in (Hassani et al., 2018). Considering the fast development of autonomous ships in recent years, this paper will briefly review the motion control methodologies, which were used for the path following of underactuated marine ships.

As discussed above, the motion control system works together with the guidance system to achieve accurately path-following control of autonomous ships, where the guidance system works like the experienced helmsman to give the desired ship's speed and the rudder command, and the motion control system will execute the command by changing the speed and heading angle. Therefore, the two systems are coupled together, and form the cascade structure, as discussed in (Fossen and Pettersen, 2014; Xu et al., 2020a).

The most popular control method for marine ships is the PID (proportional integral derivative) controller. It is a typically model-based linear control method, and the simplified steering model, such as the Nomoto model, is usually employed for the control design. However, it is also possible to generalize to the nonlinear systems by using the nonlinear manoeuvring models. The application for the path following control for marine surface ships can be found in papers (Caharija et al., 2016, 2014; Fossen, 2022; Fossen et al., 2015; Fredriksen and Pettersen, 2006; Jiang et al., 2020; Liu et al., 2017, 2016a; Moe and Pettersen, 2017, 2016; Moreira et al., 2007). The detailed design procedure and parameters tuning method will be omitted since they can be easily found in the control books.

Feedback linearization is one of the well-known methodologies that was used to control nonlinear systems. The main idea is to nonlinear system dynamics into a linear system (Freund, 1973), then the classical linear control technologies, such as pole-placement, can be used to design the control laws. The feedback linearization is also capable of the path following control of marine surface ships, the related works can be found in (Caharija et al., 2012; Moreira et al., 2007; Skjetne et al., 2011; Xu and Guedes Soares, 2016a, 2016b, 2018,, 2020, 2015), just to name a few.

The backstepping control technology was used to design a stable control law for the nonlinear systems by using the control Lyapunov functions (CLF) (Kokotović, 1992). The main idea behind the backstepping control method is to replace the control design problem using a sequence of sub-problems on lower-order systems, where the virtual control input is defined to obtain the control laws for each sub-system using control Lyapunov functions. The application of the backstepping control method for the path following control can be found in(Do et al., 2004, 2002; Fossen et al., 2003; Li et al., 2021b; Mu et al., 2018; Nie and Lin, 2019; Su et al., 2021).

In addition to the control methods mentioned above, there are also many popular control methods for the path following control of marine surface ships, such as the sliding model control (Fossen and Lekkas, 2015; Lekkas and Fossen, 2012;Li et al., 2021a, 2021b, 2019; Moe et al., 2016b), the model prediction control (Liu et al., 2018; Oh and Sun, 2010), the L1 adaptive control method (Breu and Fossen, 2011; Ren et al., 2018; Svendsen et al., 2012; Xu et al., 2021b), the dynamic surface control(Huang et al., 2021a, 2021c; Liu et al., 2016c, 2016b; Wan et al., 2020) and the fuzzy method (Li et al., 2021a; Wang et al., 2019b). Recently, the machine learning methods, such as neural networks, are also employed for the marine control system, as published in(Huang et al., 2021a, 2021b; Liu et al., 2016d; Mu et al., 2018; Rout et al., 2020; Y. Wang et al., 2019b; Wu et al., 2021).

3.3 Comparison

In this part, the comparative study of the path following control system for marine surface ships will be presented. There are 80 papers published in journals and international conferences, summarized in Table 1, using the different properties, such as control structure, results (i. e., simulation or experiment), guidance law, controller, environmental disturbance, vessel dynamics, stability properties, and underactuated control problem.

Table 1 Comparison of the path following control system for marine surface ships

No.	References	Structure	Results	Guidance law	Environmental disturbance	Controller	Vessel Dynamics	Stability	Under-actuated
1	(Do et al., 2002)	IGC	Simulation	-	No	Backstepping control	Yes	Global asymptotic stability	Yes
2	(Fossen et al., 2003)	SGC	Experiment	LOS	No	Backstepping control	Yes	Uniform global asymptotic stability	Yes
3	(Do et al., 2004)	IGC	Experiment	-	Yes	Backstepping control	Yes	Global asymptotic stability	Yes
4	(Fredriksen and Pettersen, 2006)	IGC	Experiment	LOS	Yes	Linear control method	Yes	Global κ -exponential stability	Yes
5	(Moreira et al., 2007)	SGC	Simulation	Adaptive LOS	Yes	PID	Yes	-	No
6	(Borhaug et al., 2008)	IGC	-	Integral LOS	Yes	Adaptive controllers	Yes	Global asymptotic stability	Yes
7	(Pereira et al., 2008)	SGC	Experiment	LOS	Yes	PD	No	-	No
8	(Oh and Sun, 2010)	SGC	Simulations	LOS	No	Model predictive control	Yes	-	Yes
9	(Børhaug et al., 2011)	IGC	Experiment	LOS	Yes	Feedback linearizing control	Yes	Uniform Global asymptotic stability	Yes
10	(Skjetne et al., 2011)	IGC	Simulation	LOS	No	Feedback linearizing control	Yes	Global asymptotic stability	Yes
11	(Lekkas and Fossen, 2012)	IGC	Simulation	LOS	No	Sliding mode control	Yes	Global κ -exponential stability	Yes

Table 1 Comparison of the path following control system for marine surface ships (continued)

No.	References	Structure	Results	Guidance law	Environmental disturbance	Controller	Vessel Dynamics	Stability	Under-actuated
12	(Caharija et al., 2012)	IGC	Simulation	Integral LOS	Yes	Feedback linearizing control	Yes	Uniform local exponential stability	Yes
13	(Svendsen et al., 2012)	-	Simulation	-	Yes	L1 adaptive control	No	-	No
14	(Caharija et al., 2014)	IGC	Simulation	Integral LOS	Yes	Feedback linearizing control	Yes	Uniform local exponential stability	Yes
15	(Fossen and Pettersen, 2014)	IGC	-	Proportional LOS	No	-	Yes	Uniform semiglobal exponential stability	Yes
16	(Lekkas and Fossen, 2014)	IGC	Simulation	Integral LOS	Yes	Sliding mode control	Yes	Global κ -exponential stability	Yes
17	(Fossen and Lekkas, 2015)	IGC	Simulation	Integral LOS	Yes	Sliding mode control	Yes	Global κ -exponential stability	Yes
18	(Fossen et al., 2015)	IGC	Simulation	Integral LOS	Yes	PID	Yes	Uniform semiglobal exponential stability	Yes
19	(Wiig et al., 2015)	IGC	Simulation	Integral LOS	Yes	Feedback linearizing controllers	Yes	Uniform semiglobal exponential stability	Yes
20	(Xu and Guedes Soares, 2015)	SGC	Simulation	LOS; PP+ LOS	No	PID	Yes	Global asymptotic stability	Yes
21	(Caharija et al., 2015)	-	Experiment	LOS; VF	Yes	PID	Yes	Global asymptotic stability	Yes
22	(Caharija et al., 2016)	IGC	Simulation; experimental	Integral LOS	Yes	Feedback linearizing PD controller	Yes	Globally asymptotically stable; Uniformly local exponential stable	Yes
23	(Moe and Pettersen, 2016)	SGC	Simulation	Set-based LOS	No	Adaptive feedback linearizing control	Yes	Uniform global asymptotic stability	Yes
24	(Xu and Guedes Soares, 2016a)	SGC	Simulation	VF	Yes	PID	Yes	Global asymptotic stability	Yes
25	(Niu et al., 2016)	SGC	Simulation	PP+LOS VF	Yes	PD	Yes	-	No
26	(Xu and Guedes Soares, 2016b)	SGC	Simulation	LOS; VF	Yes	PID	Yes	Global asymptotic stability	Yes
27	(Liu et al., 2016a)	SGC	Simulation	LOS	Yes	PID	Yes	Input-to-state stability	Yes

Table 1 Comparison of the path following control system for marine surface ships (continued)

No.	References	Structure	Results	Guidance law	Environmental disturbance	Controller	Vessel Dynamics	Stability	Under-actuated
28	(Liu et al., 2016b)	SGC	Simulation	Integral LOS	Yes	Dynamic surface control	Yes	Uniformly ultimately bounded	Yes
29	(Liu et al., 2016c)	SGC	Simulation	Integral LOS	Yes	Dynamic surface control	Yes	Uniformly ultimately bounded	Yes
30	(Woo and Kim, 2016)	SGC	Simulation	VF	No	-	No	-	Yes
31	(Wang et al., 2016)	SGC	Simulation	-	Yes	Adaptive robust control	Yes	Finite-time stability	No
32	(Shojaei and Dolatshahi, 2017)	SGC	Simulation	LOS	Yes	Dynamic surface control Neural networks	No	Uniformly ultimately bounded	Yes
33	(Miao et al., 2017)	SGC	Simulation	LOS	Yes	Backstepping control	Yes	Asymptotically stability	Yes
34	(Liu et al., 2017)	SGC	Simulation; experimental	LOS	Yes	PID	Yes	Input-to-state stability	Yes
35	(Moe and Pettersen, 2017)	SGC	Simulation	Set-based LOS	Yes	Feedback linearizing control	Yes	Uniform global asymptotic stability	Yes
36	(Wang et al., 2017)	SGC	Simulation	LOS	Yes	Backstepping control	Yes	Asymptotically stability	Yes
37	(Liu et al., 2018)	-	Simulation	Adaptive LOS	Yes	Model predictive control	Yes	-	Yes
38	(Mu et al., 2018)	SGC	Simulation	Adaptive LOS	Yes	Backstepping method	Yes	Uniformly ultimately bounded	Yes
39	(Yu et al., 2018)	SGC	Simulation	LOS	No	Neural network control	No	Uniformly ultimately bounded	No
40	(Xu and Guedes Soares, 2018)	SGC	Simulation	LOS; PP+ LOS	No	PID	Yes	Global asymptotic stability	Yes
41	(Mousazadeh et al., 2018)	-	Experiment	Potential field	Yes	Feedback linearizing control	Yes	-	No
42	(Huang et al., 2018)	IGC	Simulation	LOS	Yes	Sliding mode control	Yes	Uniform semiglobal exponential stability	Yes
43	(Chen et al., 2018)	IGC	Simulation	Integral LOS	Yes	Feedback linearizing control	Yes	Uniform semiglobal exponential stability	Yes
44	(Nie and Lin, 2019)	SGC	Simulation	Integral LOS	Yes	Backstepping control	Yes	Uniformly ultimately bounded	Yes

Table 1 Comparison of the path following control system for marine surface ships (continued)

No.	References	Structure	Results	Guidance law	Environmental disturbance	Controller	Vessel Dynamics	Stability	Under-actuated
45	(Li et al., 2019)	SGC	Simulation	LOS	Yes	Fuzzy logic control	No	Uniformly ultimately bounded	Yes
46	(Niu et al., 2019)	-	Experiment	LOS	No	Fuzzy logic control	No	-	No
47	(Wang et al., 2019b)	SGC	Simulation	LOS	Yes	Fuzzy logic control	No	Global asymptotic stability	Yes
48	(Wang et al., 2019c)	SGC	Simulation	LOS	Yes	PID	Yes	Input-to-state stability	No
49	(Wang et al., 2019d)	SGC	Simulation	LOS	Yes	Adaptive neural network control	No	Uniformly ultimately bounded	Yes
50	(Xu et al., 2019)	IGC	Simulation	VF	Yes	Sliding mode control	Yes	Uniform semiglobal exponential stability	Yes
51	(Wang et al., 2019a)	SGC	Simulation	-	Yes	Sliding mode control	Yes	Finite-time stability	Yes
52	(Hinostroza et al., 2019)	SGC	Simulation	VF	Yes	PID	Yes	-	Yes
53	(Sans-Muntadas et al., 2019)	IGC	Experiment	-	Yes	PID	No	asymptotically stability	No
54	(Weng et al., 2020)	SGC	Simulation	LOS	Yes	Sliding mode control	Yes	Ultimately bounded	No
55	(Bejarano and N-Yo, 2020)	SGC	Simulation	LOS	Yes	Backstepping control	Yes	Stable	Yes
56	(Xu et al., 2020a)	IGC	Simulation	VF	Yes	Sliding mode control	Yes	Uniform semiglobal exponential stability	Yes
57	(Wan et al., 2020)	SGC	Simulation	Integral LOS	No	Dynamic surface control	Yes	Uniformly asymptotically stability	Yes
58	(Rout et al., 2020)	SGC	Simulation Experiment	Modified LOS	Yes	Adaptive neural network controller	Yes	Uniformly ultimately bounded	Yes
59	(Jiang et al., 2020)	SGC	Simulation Experiment	LOS	Yes	PID	Yes	Global asymptotic stability	Yes
60	(Xu and Guedes Soares, 2020)	SGC	Simulation	LOS; VF	Yes	PID	Yes	Global asymptotic stability	Yes
61	(Nie and Lin, 2020)	SGC	Simulation	LOS	Yes	Fuzzy logic control	No	uniform ultimate bounded	No
62	(Wen et al., 2020)	SGC	Experiment	VF	Yes	Feedback control	Yes	Semi-global exponential stable	Yes
63	(Wu et al., 2021)	SGC	Experiment	LOS	Yes	Neural network controller	No	Input-to-state stability	Yes

Table 1 Comparison of the path following control system for marine surface ships (continued)

No.	References	Structure	Results	Guidance law	Environmental disturbance	Controller	Vessel Dynamics	Stability	Under-actuated
64	(Su et al., 2021)	SGC	Simulation	LOS	NO	Backstepping method	Yes	Uniformly ultimately bounded	No
65	(Xu et al., 2021a)	IGC	Simulation Experiment	VF	Yes	Sliding mode control	Yes	Uniform semiglobal exponential stability	Yes
66	(Liu et al., 2021)	SGC	Experiment	LOS	Yes	PID	No	-	No
67	(Tian et al., 2021)	SGC	Simulation	LOS	Yes	Model predictive control	Yes	Stable	No
68	(Xu et al., 2021b)	IGC	Simulation	VF	Yes	L1 adaptive control	Yes	Uniform semiglobal exponential stability	Yes
69	(Hinostroza et al., 2021)	SGC	Experiment	LOS	Yes	PID	Yes	-	Yes
70	(Li et al., 2021a)	SGC	Simulation	Integral LOS	Yes	Sliding mode control	Yes	Uniformly ultimately bounded	Yes
71	(Li et al., 2021b)	IGC	Simulation	LOS	Yes	Backstepping sliding mode control	Yes	Uniformly global finite-time stability	No
72	(Min and Zhang, 2021)	IGC	Simulation	LOS	Yes	Fuzzy logic control	Yes	Uniformly ultimately bounded	Yes
73	(Abrougui et al., 2021)	SGC	Experiment	-	Yes	Sliding mode control	No	-	Yes
74	(Zhang et al., 2021)	SGC	Simulation	LOS	No	Feedback control	Yes	Global asymptotic stability	No
75	(Fossen, 2022)	SGC	Simulation	Proportional LOS	Yes	PID	Yes	Uniformly semi-globally asymptotically stability	No
76	(Song et al., 2022)	SGC	Simulation Experiment	VF	Yes	PID	Yes	-	No
77	(G. Zhang et al., 2022)	SGC	Simulation	Artificial potential field	Yes	Backstepping method	Yes	Semi-globally uniform ultimate bounded	Yes
78	(Jiang et al., 2022)	SGC	Simulation	-	Yes	MPC	No	Input-to-state stable	No
79	(H. Zhang et al., 2022)	SGC	Simulation	-	Yes	Sliding mode control	Yes	Stable	Yes
80	(Wang et al., 2022)	SGC	Simulation	LOS+fast marching method	Yes	deep reinforcement learning	Yes	Stable	Yes

There are two typical approaches for the design of the guidance and control system to solve the path following problem: The separated Guidance and Control (SGC) approach and the Integrated Guidance and Control (IGC) approach (Rubí et al., 2020). The Separated Guidance and Control (SGC) approach, consists of an outer-loop guidance law for the generation of the desired heading angle and an inner-loop controller to track the desired heading angle and generated the output rudder angle. The stability property of the whole system is carried out for the outer and inner loop separately, and the coupled term is neglected. The Integrated Guidance and Control (IGC) approach combines the guidance and control system, and the whole system is a cascade where the heading control system is the driving system and the guidance system is the driven system, as presented in Figure 10. As can be observed, the heading control error will affect the convergence of the guidance system, which is to minimize the cross-track error, therefore, the coupled term is considered in the Integrated Guidance and Control approach. From table 1. the distribution of the control structure using the SGC and IGC approach is presented in Figure 11. About 62% of papers choose the SGC approach for simplifying the stability analysis, and 38% use the IGC approach.

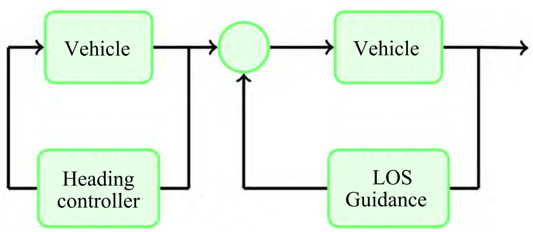

Figure 10 The cascaded path following control system (Lekkas and Fossen, 2014, 2012)

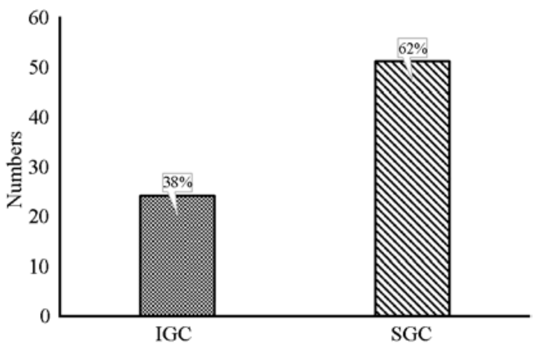

Figure 11 The distribution of the control structure

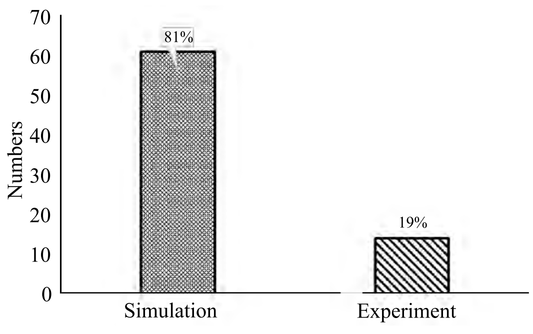

Figure 12 The validation methods

The results are usually validated using the simulations and experiments using the free-running ship model (Xu et al., 2020b). Right now, a large number of papers (81%) are using the simulation for the validation of the path following control, whereas only 19% of papers, the experimental studies were carried out, as indicated in Figure 12. Currently, most experimental studies are carried out using scale ship models in the lab or outdoor water area. The experimental tests in the lab can provide high accuracy position and velocity with the aid of an advanced position measurement system, meanwhile, the environmental disturbance (wind, wave and current) can also be scaled according to the ship model and can be controlled during the tests. There are some experimental works carried out in the laboratory, such as (Fossen et al., 2003; Fredriksen and Pettersen, 2006). The most convenient way to validate the path-following control system for Maritime Autonomous Surface Ships is using the scaled ship models in the outdoor water area. The sensors for the measurement of the position and velocity and actuators are needed to installed on the ship model, and a data acquisition system and remote communication system is also needed for the data measurement and storage. Some interested works on the autonomous ship model can be found in (Liu et al., 2017; Mousazadeh et al., 2018; Niu et al., 2019; Rout et al., 2020; Sans-Muntadas et al., 2019; Wen et al., 2020; Wu et al., 2021;Xu et al., 2021a, 2020b; Zhu et al., 2020), just to name a few.

As discussed above, there are 4 typical guidance laws, but only LOS and VF guidance laws are widely used for the path following control of marine surface ships, as presented in Figure 13. Right now, LOS and its revised versions take the leading position (about 63%) in the published papers due to the simple structure and easy implementation. The integral LOS (18%) is also widely used for cancelling the drift angle due to environmental disturbance. The VF guidance law (13%) is a novel method for the marine surface ship and it is still under fast development and provides good control performance (Caharija et al., 2015).

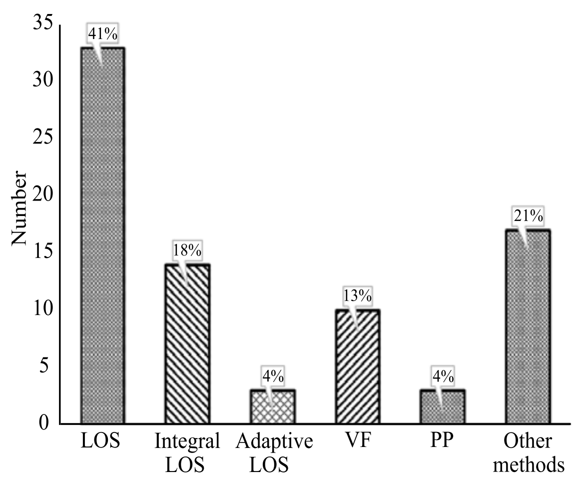

Figure 13 The distribution of the guidance laws

Right now, there are many controllers used to solve the path following problem, both linear controllers and nonlinear controllers, such as proportional-integral-derivative

(PID) controller, Linear control method, backstepping control, sliding mode control, feedback linearizing control, sliding mode control, adaptive control, as presented in Figure 14. They are usually designed based on linear or nonlinear ship dynamics, well-known as model-based control methodology. PID controller is still popular in the reviewed papers (27%), considering its simple structure and easy implementation.

The nonlinear controllers, such as backstepping control (12%), feedback linearizing control (15%) and sliding mode control (20%) rank second in the reviewed papers. It is worth mentioning that there are some mode-free control methods, such as Neural network control (5%), Fuzzy logic control (8%). They also provide a good tracking performance, and the stability properties are still a challenge for those control methods.

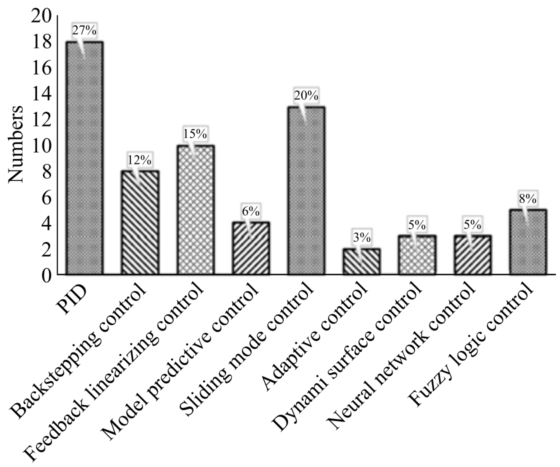

Figure 14 The distribution of the control design technologies

As can be observed from Table 1 and Figure 15, most of the papers provide the stability proof for their control, such as uniformly ultimately bounded (22%), Finite-time stability (6%), Input-to-state stability (7%), global asymptotic stability (37%), uniformly local exponential stability (4%), globally κ -exponentially stability (7%), and Uniform semi-global exponential stability (17%).

Stability is the most important property of any control system from a control-theoretic perspective since it is closely related to the safety, robustness, and reliability of robotic systems. Global exponential stability (GES) is usually the most desired quality of a closed-loop control system (Khalil, 2002; Loría and Panteley, 2005), but, it cannot be achieved due to the structural properties of the cross-track error (Fossen and Pettersen, 2014). The uniform semi-global exponential stability (USGES) is slightly weaker than GES and it is important for the performance and robustness of the control system under environmental disturbance. In Table 1 and Figure 16, most papers will consider the environmental disturbances (81%), such as wind, waves, and currents, the vessel dynamic (81%) and underactuated motions (75%) of marine surface ships.

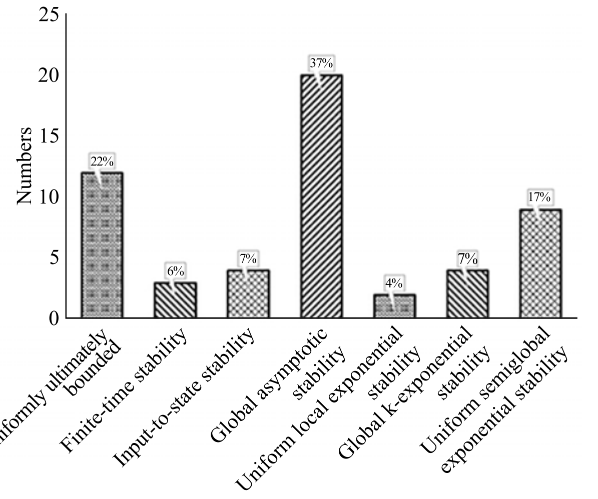

Figure 15 The distribution of the stability of the closed-loop system

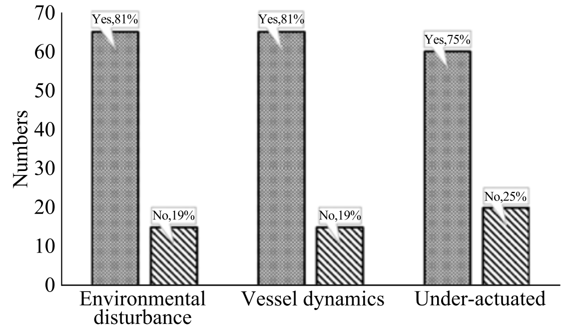

Figure 16 The distribution of the environmental disturbance, vessel dynamics and underactuated dynamics

4 Conclusions

The path following control system is one of the most critically important systems for marine autonomous surface ships since it guarantees that the autonomous ship can follow the predefined path with small cross-track errors. This paper reviews the path following control systems, more precisely, guidance systems and control systems, for marine autonomous surface ships. The path following control problem and control objectives are firstly defined and the cross-track errors function is derived using the kinematic equations of marine surface ships. Then, the paper describes the most widely used guidance laws, such as LOS and modified version, PP, constant bearing and VF guidance law. The control methodologies, such as PID, feedback linearization, backstepping method, sliding mode control and neural network-based control are briefly introduced.

To compare the state-of-the-art of path-following control for autonomous ships, 80 papers published in journals and international conferences are carefully selected and analysed. Several properties and characteristics are defined, such as the control structure, guidance laws, control method, stability results, environmental disturbance and vessel dynamics, just to name a few.

The conclusions can be summarized:

(1) Most of the papers (62%) choose the separated guidance and control (SGC) for the design of the path following control system.

(2) Simulations are still the main means for validation, taking up almost 81% of the selected papers. Experimental studies are still very challenging due to many factors, such as the laboratory facility, sensor technology, model scale effect, test location and environmental disturbance, just to name a few.

(3) LOS and its extended versions take the leading position (about 63%) in the selected papers due to the simple structure and easy implementation.

(4) The linear model-based PID controller is still popular in the reviewed papers (27%), and nonlinear control technologies, such as Feedback linearizing, backstepping control and sliding mode control are also widely used in the selected papers.

(5) Most papers provide stability proof for the proposed system, and the global asymptotic stability proof (37%) was proved in most papers.

(6) The environmental disturbance (88%), vessel dynamics (84%) and underactuated motion (79%) are considered for most papers. The wind, wave and current are the typical disturbance considered in the selected paper. The vessel dynamic is typically considered for the model-based control design, and the model-free control method, such as fuzzy logic control, and neutral network control, usually neglected the vessel dynamics.

In the future, the following works on path following control of underactuatd marine surface ships are recommented. The integrated Guidance and Control (IGC) approach is recommended for the design of the guidance and control for autonomous surface ships, especially the low speed commercial ships, because the coupled terms are neglected in the separated guidance and control (SGC) approach. LOS guidance law can provide a good performance and is still recommented. The vector field guidance law is expansible and easy to implement for collision avoidance, but its stability still needs to be investigated. The autonomous ship model is recommended for validation, but the sea trials of autonomous ships are still necessary for the development of automatic control systems.

Competing interest C. Guedes Soares is an editorial board member for the Journal of Marine Science and Application and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

References

Abkowitz MA (1980) Measurement of hydrodynamic characteristics from ship maneuvering trials by system identification. SNAME Trans. 88, 283-318

Abrougui H, Nejim S, Hachicha S, Zaoui C, Dallagi H (2021) Modeling, parameter identification, guidance and control of an unmanned surface vehicle with experimental results. Ocean Eng. 241, 110038. https://doi.org/10.1016/J.OCEANENG.2021.110038

Allianz Global Corporate and Speciality (2018) Safety and Shipping Review 2018. Munich, Germany

Bejarano G, N-Yo S (2020) Velocity estimation and robust nonlinear path following control of autonomous surface vehicles. IFAC-PapersOnLine 53, 14674-14679. https://doi.org/10.1016/J.IFACOL.2020.12.1479

Børhaug E, Pavlov A, Panteley E, Pettersen KY (2011) Straight line path following for formations of underactuated marine surface vessels. IEEE Trans. Control Syst. Technol. 19, 493-506. https://doi.org/10.1109/TCST.2010.2050889

Børhaug E, Pavlov A, Pettersen KY (2008) Integral LOS control for path following of underactuated marine surface vessels in the presence of constant ocean currents. In: 47th IEEE Conference on Decision and Control, 4984-4991. https://doi. org/10.1109/CDC.2008.4739352

Breivik M, Fossen T (2009) Guidance laws for autonomous underwater vehicles. In: inzartsev AV Ed. Underwater Vehicles. IntechOpen, London. https://doi.org/10.5772/6696

Breu DA, Fossen TI (2011) L_1 adaptive and extremum seeking control applied to roll parametric resonance in ships. IEEE Int. Conf. Control Autom. ICCA, 871876. https://doi. org/10.1109/ICCA.2011.6138047

Caharija W, Candeloro M, Pettersen KY, Sørensen AJ (2012) Relative velocity control and integral LOS for path following of underactuated surface vessels. IFAC Proc. Vol. 45, 380-385. https://doi.org/10.3182/20120919-3-IT-2046.00065

Caharija W, Pettersen KY, Bibuli M, Calado P, Zereik E, Braga J, Gravdahl JT, Sorensen AJ, Milovanovic M, Bruzzone G (2016) Integral line-of-sight guidance and control of underactuated marine vehicles: theory, simulations, and experiments. IEEE Trans. Control Syst. Technol. 24, 1623-1642. https://doi.org/10.1109/TCST.2015.2504838

Caharija W, Pettersen KY, Calado P, Braga J (2015) A comparison between the ILOS guidance and the vector field guidance. In: IFAC-PapersOnLine. Elsevier, 89-94. https://doi. org/10.1016/j.ifacol.2015.10.263

Caharija W, Pettersen KY, Sørensen AJ, Candeloro M, Gravdahl JT (2014) Relative velocity control and integral line of sight for path following of autonomous surface vessels: merging intuition with theory. Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. 228, 180-191. https://doi. org/10.1177/1475090213512293

Chen X, Liu Z, Zhang J, Zhou D, Dong J (2018) Adaptive sliding-mode path following control system of the underactuated USV under the influence of ocean currents. J. Syst. Eng. Electron. 29, 1271-1283. https://doi.org/10.21629/JSEE.2018.06.14

Cho N, Kim Y, Park S (2015) Three-dimensional nonlinear differential geometric path-following guidance law. https://doi.org/10.2514/1.G001060

Do KD, Jiang ZP, Pan J (2002) Underactuated ship global tracking under relaxed conditions. IEEE Trans. Automat. Contr. 47, 1529-1536. https://doi.org/10.1109/TAC.2002.802755

Do KD, Jiang ZP, Pan J (2004) Robust adaptive path following of underactuated ships. Automatica 40, 929-944. https://doi. org/10.1016/j.automatica.2004.01.021

Faltinsen OM (1993) Sea Loads on Ships and Offshore Structures,

Cambridge University Press. Cambridge, UK.
Fossen TI (2011) Handbook of Marine Craft Hydrodynamics and Motion Control. John Wiley & Sons, Ltd, Chichester, UK. https://doi.org/10.1002/9781119994138
Fossen TI (2022) Line-of-sight path-following control utilizing an extended Kalman filter for estimation of speed and course over ground from GNSS positions. J. Mar. Sci. Technol. 1-8. https://doi.org/10.1007/S00773-022-00872-Y/FIGURES/8
Fossen TI, Breivik M, Skjetne R (2003) Line-of-sight path following of underactuated marine craft. IFAC Proc. Vol. 36, 211-216. https://doi.org/10.1016/S1474-6670(17)37809-6
Fossen TI, Lekkas AM (2015) Direct and indirect adaptive integral line-of-sight path-following controllers for marine craft exposed to ocean currents. Int. J. Adapt. Control Signal Process. 31, 445-463. https://doi.org/10.1002/acs.2550
Fossen TI, Pettersen KY (2014) On uniform semiglobal exponential stability (USGES) of proportional line-of-sight guidance laws. Automatica 50, 2912-2917. https://doi.org/10.1016/J.AUTOMATICA.2014.10.018
Fossen TI, Pettersen KY, Galeazzi R (2015) Line-of-sight path following for dubins paths with adaptive sideslip compensation of drift forces. IEEE Trans. Control Syst. Technol. 23, 820-827. https://doi.org/10.1109/TCST.2014.2338354
Fredriksen E, Pettersen KY (2006) Global κ-exponential way-point maneuvering of ships: theory and experiments. Automatica 42, 677-687. ttps://doi.org/10.1016/J.AUTOMATICA.2005.12.020
Freund E (1973) Decoupling and pole assignment in nonlinear systems. Electron. Lett. 9, 373-374. https://doi. org/10.1049/EL:19730275
Gu N, Wang D, Peng Z, Wang J, Han QL (2022a) Advances in Line-of-Sight Guidance for Path Following of Autonomous Marine Vehicles: an Overview. IEEE Trans. Syst. Man, Cybern. Syst. https://doi.org/10.1109/TSMC.2022.3162862
Gu N, Wang D, Peng Z, Wang J, Han QL (2022b) Disturbance observers and extended state observers for marine vehicles: a survey. Control Eng. Pract. 123, 105158. https://doi.org/10.1016/J.CONENGPRAC.2022.105158
Hassani V, Pascoal AM, Onstein TF (2018) Data-driven control in marine systems. Annu. Rev. Control 46, 343-349. https://doi.org/10.1016/J.ARCONTROL.2018.10.006
Hinostroza MA, Xu H, Guedes Soares C (2021) Experimental results of the cooperative operation of autonomous surface vehicles navigating in complex marine environment. Ocean Eng. 219, 108256. https://doi.org/10.1016/j.oceaneng.2020.108256
Hinostroza MA, Xu H, Guedes Soares C (2019) Cooperative operation of autonomous surface vehicles for maintaining formation in complex marine environment. Ocean Eng. 183, 132-154. https://doi.org/10.1016/j.oceaneng.2019.04.098
Huang C, Zhang X, Zhang G (2021a) Decentralized event-triggered cooperative path-following control for multiple autonomous surface vessels under actuator failures. Appl. Ocean Res. 113, 102751. https://doi.org/10.1016/J.APOR.2021.102751
Huang C, Zhang X, Zhang G (2021b) Adaptive neural finite-time formation control for multiple underactuated vessels with actuator faults. Ocean Eng. 222, 108556. https://doi.org/10.1016/J.OCEANENG.2020.108556
Huang C, Zhang X, Zhang G, Deng Y (2021c) Robust practical fixed-time leader-follower formation control for underactuated autonomous surface vessels using event-triggered mechanism. Ocean Eng. 233, 109026. https://doi.org/10.1016/J.OCEANENG.2021.109026
Huang H, Li Y, Zhuang Y, Gong M, Sharma S, Xu D (2018) Line-of-sight path following of an underactuated USV exposed to ocean currents using cascaded theorem. 2018 WRC Symp. Adv. Robot. Autom. WRC SARA 2018 - Proceeding 334-339. https://doi.org/10.1109/WRC-SARA.2018.8584241
IMO, Autonomous ships: regulatory scoping exercise completed [WWW Document]. URL https://www.imo.org/en/MediaCentre/PressBriefings/pages/MASSRSE2021.aspx (accessed 5.9.22).
Jiang Y, Peng Z, Meng C, Liu L, Wang D, Li T (2022) Data-driven finite control set model predictive speed control of an autonomous surface vehicle subject to fully unknown kinetics and propulsion dynamics. Ocean Eng. 264, 112474. https://doi. org/10.1016/J.OCEANENG.2022.112474
Jiang Y, Peng Z, Wang D, Chen CLP (2020) Line-of-sight target enclosing of an underactuated autonomous surface vehicle with experiment results. IEEE Trans. Ind. Informatics 16, 832-841. https://doi.org/10.1109/TII.2019.2923664
Khalil HK (2002) Nonlinear Systems. Prentice Hall
Kokotović PV (1992) The Joy of Feedback: Nonlinear and Adaptive. IEEE Control Syst. 12, 7-17. https://doi.org/10.1109/37.165507
Lekkas AM, Fossen TI (2014) Integral LOS path following for curved paths based on a monotone cubic hermite spline parametrization. IEEE Trans. Control Syst. Technol. 22, 2287-2301. https://doi.org/10.1109/TCST.2014.2306774
Lekkas AM, Fossen TI (2012) A time-varying lookahead distance guidance law for path following. IFAC Proc. Vol. 45, 398-403. https://doi.org/10.3182/20120919-3-IT-2046.00068
Li M, Guo C, Yu H (2019) Filtered Extended State Observer Based Line-of-Sight Guidance for Path following of Unmanned Surface Vehicles with Unknown Dynamics and Disturbances. IEEE Access 7, 178401-178412. https://doi.org/10.1109/ACCESS.2019.2958855
Li M, Guo C, Yu H (2021a) Extended state observer-based integral line-of-sight guidance law for path following of underactuated unmanned surface vehicles with uncertainties and ocean currents. Int. J. Adv. Robot. Syst. 18, 172988142110110. https://doi. org/10.1177/17298814211011035
Li M, Guo C, Yu H, Yuan Y (2021b) Line-of-sight-based global finite-time stable path following control of unmanned surface vehicles with actuator saturation. ISA Trans. https://doi. org/10.1016/j.isatra.2021.07.009
Lim S, Jung W, Bang H (2014) Vector field guidance for path following and arrival angle control, in: 2014 International Conference on Unmanned Aircraft Systems, ICUAS 2014 - Conference Proceedings. IEEE, pp. 329-338. https://doi. org/10.1109/ICUAS.2014.6842271
Liu C, Negenborn RR, Chu X, Zheng H (2018) Predictive path following based on adaptive line-of-sight for underactuated autonomous surface vessels. J. Mar. Sci. Technol. 23, 483-494. https://doi.org/10.1007/S00773-017-0486-2/FIGURES/11
Liu L, Wang D, Pen, Z (2017) ESO-based line-of-sight guidance law for path following of underactuated marine surface vehicles with exact sideslip compensation. IEEE J. Ocean. Eng. 42, 477-487. https://doi.org/10.1109/JOE.2016.2569218
Liu L, Wang D, Peng Z (2016a) ESO-based line-of-sight guidance law for straight line path following with exact sideslip compensation. Proc. World Congr. Intell. Control Autom. 2016-September, 677-681. https://doi.org/10.1109/WCICA.2016.7578426
Liu L, Wang D, Peng Z (2016b) Path following of marine surface vehicles with dynamical uncertainty and time-varying ocean disturbances. Neurocomputing 173, 799-808. https://doi.org/10.1016/J.NEUCOM.2015.08.033
Liu L, Wang D, Peng Z (2016c) Predictor-based line-of-sight guidance law for path following of underactuated marine surface vessels. Proc. 6th Int. Conf. Intell. Control Inf. Process. ICICIP 2015 284-288. https://doi.org/10.1109/ICICIP.2015.7388184
Liu L, Wang D, Peng Z (2016d) Path following of marine surface vehicles with dynamical uncertainty and time-varying ocean disturbances. Neurocomputing 173, 799-808. https://doi. org/10.1016/J.NEUCOM.2015.08.033

Liu Z, Yu L, Xiang Q, Qian T, Lou Z, Xue W (2021) Research on USV trajectory tracking method based on LOS algorithm. Proc. - 2021 14th Int. Symp. Comput. Intell. Des. Isc. 2021 408-411. https://doi.org/10.1109/ISCID52796.2021.00098

Loría A, Panteley E (2005) Cascaded Nonlinear Time-Varying Systems: Analysis and Design, in: Lamnabhi-Lagarrigue, F., Loría, A., Panteley, E. (Eds.), Advanced Topics in Control Systems Theory: Lecture Notes from FAP 2004. Springer London, London, 23-64. https://doi.org/10.1007/11334774_2

Maritime K (2016) World's First Official Test Bed for Autonomous Shipping Opens in Norway [WWW Document]. URL https://www.km.kongsberg.com/ks/web/nokbg0238.nsf/AllWeb/166309633F206651C125804200250951?OpenDocument (accessed 9.6.18).

MARKETS&MARKETS (2021) Autonomous Ships Market by Autonomy, Ship Type, End-Use | COVID-19 Impact Analysis | MarketsandMarketsTM [WWW Document]. URL https://www.marketsandmarkets. com/Market-Reports/autonomous-ships-market-267183224.html (accessed 4.2.21).

Miao J, Wang S, Tomovic MM, Zhao Z (2017) Compound line-of-sight nonlinear path following control of underactuated marine vehicles exposed to wind, waves, and ocean currents. Nonlinear Dyn. 89, 2441-2459. https://doi.org/10.1007/S11071-017-3596-9/FIGURES/11

Min B, Zhang X (2021) Concise robust fuzzy nonlinear feedback track keeping control for ships using multi-technique improved LOS guidance. Ocean Eng. 224, 108734. https://doi.org/10.1016/J.OCEANENG.2021.108734

Moe S, Pettersen KY (2017) Set-Based line-of-sight (LOS) path following with collision avoidance for underactuated unmanned surface vessels under the influence of ocean currents. 1st Annu. IEEE Conf. Control Technol. Appl. CCTA 2017 2017-January, 241-248. https://doi.org/10.1109/CCTA.2017.8062470

Moe S, Pettersen KY (2016) Set-based Line-of-Sight (LOS) path following with collision avoidance for underactuated unmanned surface vessel, in: 24th Mediterranean Conference on Control and Automation, MED 2016. pp. 402-409. https://doi. org/10.1109/MED.2016.7535964

Moe S, Pettersen KY, Fossen TI, Gravdahl JT (2016a) Line-of-sight curved path following for underactuated USVs and AUVs in the horizontal plane under the influence of ocean currents. In: 24th Mediterranean Conference on Control and Automation, MED 2016: 38-45. https://doi.org/10.1109/MED.2016.7536018

Moe S, Pettersen KY, Fossen TI, Gravdahl JT (2016b) Line-of-sight curved path following for underactuated USVs and AUVs in the horizontal plane under the influence of ocean currents. 24th Mediterr. Conf. Control Autom. MED, 38-45. https://doi. org/10.1109/MED.2016.7536018

Moreira L, Fossen TI, Guedes Soares C (2007) Path following control system for a tanker ship model. Ocean Eng. 34, 2074-2085. https://doi.org/10.1016/j.oceaneng.2007.02.005

Mousazadeh H, Jafarbiglu H, Abdolmaleki H, Omrani E, Monhaseri F, Abdollahzadeh M Reza, Mohammadi-Aghdam A, Kiapei A, Salmani-Zakaria Y, Makhsoos A (2018) Developing a navigation, guidance and obstacle avoidance algorithm for an Unmanned Surface Vehicle (USV) by algorithms fusion. Ocean Eng. 159, 56-65. https://doi.org/10.1016/j.oceaneng.2018.04.018

Mu D, Wang G, Fan Y, Bai Y, Zhao Y (2018) Fuzzy-based optimal adaptive line-of-sight path following for underactuated unmanned surface vehicle with uncertainties and time-varying disturbances. Math. Probl. Eng. 2018. https://doi.org/10.1155/2018/7512606

Nelson DR, Barber DB, McLain TW, Beard RW (2006) Vector field path following for small unmanned air vehicles. 2006 Am. Control Conf. 5788-5794. https://doi.org/10.1109/ACC.2006.1657648

Nelson DR, Barber DB, McLain TW, Beard RW (2007) Vector field path following for miniature air vehicles. IEEE Trans. Robot. 23, 519-529. https://doi.org/10.1109/TRO.2007.898976

Nie J, Lin X (2019) Improved adaptive integral line-of-sight guidance law and adaptive fuzzy path following control for underactuated MSV. ISA Trans. 94, 151-163. https://doi.org/10.1016/J.ISATRA. 2019.04.010

Nie J, Lin X (2020) FAILOS guidance law based adaptive fuzzy finite-time path following control for underactuated MSV. Ocean Eng. 195, 106726. https://doi.org/10.1016/J.OCEANENG.2019.106726

Niu G, Wan L, Zou J, Zeng J, Fan J, Sun C (2019) Intelligent path-following control of unmanned surface vehicles based on improved line-of-sight guidance. IOP Conf. Ser. Mater. Sci. Eng. 677, 042104. https://doi.org/10.1088/1757-899X/677/4/042104

Niu H, Lu Y, Savvaris A, Tsourdos A (2016) Efficient path following algorithm for unmanned surface vehicle. Ocean. 2016 - Shanghai. https://doi.org/10.1109/OCEANSAP.2016.7485430

Nomoto K, Taguchi T, Honda K, Hirano S (1957) On the steering qualities of ships. Int. Shipbuild. Prog. 4, 354-370.

Oh S-R, Sun J (2010) Path following of underactuated marine surface vessels using line-of-sight based model predictive control. Ocean Eng. 37, 289-295. https://doi.org/10.1016/j.oceaneng.2009.10.004

Papoulias FA (1993) On the nonlinear dynamics of pursuit guidance for marine vehicles. J. Sh. Res. 37, 342-353. https://doi. org/10.5957/JSR.1993.37.4.342

Pereira A, Das J, Sukhatme GS (2008) An experimental study of station keeping on an underactuated ASV. 2008 IEEE/RSJ Int. Conf. Intell. Robot. Syst. IROS 3164-3171. https://doi. org/10.1109/IROS.2008.4650991

Ren RY, Zou ZJ, Wang YD, Wang XG (2018) Adaptive Nomoto model used in the path following problem of ships. J. Mar. Sci. Technol. 1-11. https://doi.org/10.1007/s00773-017-0518-y

Roberts GN (2008) Trends in marine control systems. Annu. Rev. Control 32, 263-269. https://doi.org/10.1016/J.ARCONTROL.2008.08.002

Rolls-Royce (2015) Rolls-Royce to Lead Autonomous Ship Research Project [WWW Document]. URL https://www. rolls-royce. com/media/our-stories/press-releases/2015/pr-02-07-15-rolls-royce-to-lead-autonomous-ship-research-project.aspx (accessed 9.6.18).

Rout R, Cui R, Han Z (2020) Modified line-of-sight guidance law with adaptive neural network control of underactuated marine vehicles with state and input constraints. IEEE Trans. Control Syst. Technol. 28, 1902-1914. https://doi.org/10.1109/TCST.2020.2998798

Rubí B, Pérez R, Morcego B (2020) A Survey of Path Following Control Strategies for UAVs Focused on Quadrotors. J. Intell. Robot. Syst. Theory Appl. 98, 241-265. https://doi. org/10.1007/s10846-019-01085-z

Sans-Muntadas A, Kelasidi E, Pettersen KY, Brekke E (2019) Path planning and guidance for underactuated vehicles with limited field-of-view. Ocean Eng. 174, 84-95. https://doi. org/10.1016/J.OCEANENG.2019.01.027

Shojaei K, Dolatshahi M (2017) Line-of-sight target tracking control of underactuated autonomous underwater vehicles. Ocean Eng. 133, 244-252. https://doi.org/10.1016/j.oceaneng.2017.02.007

Skjetne R, Jørgensen U, Teel AR (2011) Line-of-sight path-following along regularly parametrized curves solved as a generic maneuvering problem. Proc. IEEE Conf. Decis. Control 2467-2474. https://doi.org/10.1109/CDC.2011.6161364

Song D, Gan W, Yao P, Zang W, Zhang Z, Qu X (2022) Guidance and control of autonomous surface underwater vehicles for target tracking in ocean environment by deep reinforcement learning. Ocean Eng. 250, 110947. https://doi.org/10.1016/j.oceaneng.2022.110947

Su Y, Wan L, Zhang D, Huang F (2021) An improved adaptive integral line-of-sight guidance law for unmanned surface vehicles with uncertainties. Appl. Ocean Res. 108, 102488. https://doi.org/10.1016/J.APOR.2020.102488

Sutulo S, Guedes Soares C (2011) Mathematical models for simulation of manoeuvring performance of ships. In: Guedes Soares C, et al

(Eds). Maritime Engineering and Technology. Taylor & Francis Group, London, 661–698. https://doi.org/10.13140/2.1.3538.7209

Svendsen CH, Holck NO, Galeazzi R, Blanke M (2012) L1 adaptive manoeuvring control of unmanned high-speed water craft. IFAC Proc. Vol. 45, 144-151. https://doi.org/10.3182/20120919-3-IT-2046.00025

Tian Z, Zheng H, Xu W (2021) Path following of autonomous surface vehicles with line-of-sight and nonlinear model predictive control. 6th Int. Conf. Transp. Inf. Saf. New Infrastruct. Constr. Better Transp. ICTIS 2021 1269-1274. https://doi. org/10.1109/ICTIS54573.2021.9798580

Wan L, Su Y, Zhang H, Shi B, AbouOmar MS (2020) An improved integral light-of-sight guidance law for path following of unmanned surface vehicles. Ocean Eng. 205, 107302. https://doi.org/10.1016/J.OCEANENG.2020.107302

Wang N, Karimi HR, Li H, Su SF (2019a) Accurate Trajectory Tracking of Disturbed Surface Vehicles: A Finite-Time Control Approach. IEEE/ASME Trans. Mechatronics 24, 1064-1074. https://doi.org/10.1109/TMECH.2019.2906395

Wang N, Qian C, Sun J-C, Liu Y-C (2016) Adaptive Robust Finite-Time Trajectory Tracking Control of Fully Actuated Marine Surface Vehicles. IEEE Trans. Control Syst. Technol. 24, 1454-1462. https://doi.org/10.1109/TCST.2015.2496585

Wang N, Sun Z, Yin J, Zou Z, Su SF (2019b) Fuzzy unknown observer-based robust adaptive path following control of underactuated surface vehicles subject to multiple unknowns. Ocean Eng. 176, 57-64. https://doi.org/10.1016/J.OCEANENG.2019.02.017

Wang N, Sun Z, Yin J, Zheng Z (2017) Surge-varying LOS based path following control of underactuated marine vehicles with accurate disturbance observation, in: 2017 IEEE 7th International Conference on Underwater System Technology: Theory and Applications (USYS). IEEE, 1-6. https://doi.org/10.1109/USYS.2017.8309464

Wang S, Yan X, Ma F, Wu P, Liu Y (2022) A novel path following approach for autonomous ships based on fast marching method and deep reinforcement learning. Ocean Eng. 257, 111495. https://doi.org/10.1016/J.OCEANENG.2022.111495

Wang Y, Tong H, Fu M (2019c) Line-of-sight guidance law for path following of amphibious hovercrafts with big and time-varying sideslip compensation. Ocean Eng. 172, 531-540. https://doi. org/10.1016/J.OCEANENG.2018.12.036

Wang Y, Tong H, Wang C (2019d) High-gain observer-based line-of-sight guidance for adaptive neural path following control of underactuated marine surface vessels. IEEE Access 7, 26088-26101. https://doi.org/10.1109/ACCESS.2019.2900365

Wen Y, Tao W, Zhu M, Zhou J, Xiao C (2020) Characteristic model-based path following controller design for the unmanned surface vessel. Appl. Ocean Res. 101, 102293. https://doi. org/10.1016/J.APOR.2020.102293

Weng Y, Wang N, Guedes Soares C (2020) Data-driven sideslip observer-based adaptive sliding-mode path-following control of underactuated marine vessels. Ocean Eng. 197, 106910. https://doi.org/10.1016/J.OCEANENG.2019.106910

Wiig MS, Pettersen KY, Krogstad TR (2015) Uniform Semiglobal Exponential Stability of Integral Line-of-Sight Guidance Laws. IFAC-PapersOnLine 48, 61-68. https://doi.org/10.1016/J.IFACOL.2015.10.259

Woo J, Kim N (2016) Vector field based guidance method for docking of an unmanned surface vehicle. In: The Twelfth ISOPE Pacific/Asia Offshore Mechanics Symposium. Gold Coast, Australia, p. ISOPE-P-16-103.

Wu W, Peng Z, Wang D, Liu L, Han Q-L (2021) Network-Based Line-of-Sight Path Tracking of Underactuated Unmanned Surface Vehicles With Experiment Results. IEEE Trans. Cybern. 1-11. https://doi.org/10.1109/TCYB.2021.3074396

Xu H, Fossen TI, Guedes Soares C (2020a) Uniformly semiglobally exponential stability of vector field guidance law and autopilot for path-following. Eur. J. Control 53, 88-97. https://doi. org/10.1016/j.ejcon.2019.09.007

Xu H, Guedes Soares C (2015) An optimized path following algorithm for a surface ship model. In: Guedes Soares, C., et al. (Eds.). Towards Green Marine Technology and Transport. CRC Press, 151-158. https://doi.org/10.1201/b18855-21

Xu H, Guedes Soares C (2016a) Vector field path following for surface marine vessel and parameter identification based on LS-SVM. Ocean Eng. 113, 151-161. https://doi.org/10.1016/j.oceaneng.2015.12.037

Xu H, Guedes Soares C (2016b) Waypoint-following for a marine surface ship model based on vector field guidance law. In: Guedes Soares C., et al. (Eds.). Maritime Technology and Engineering 3. Taylor & Francis Group, London, 409-418

Xu H, Guedes Soares C (2018) An optimized energy-efficient path following algorithm for underactuated marine surface ship model. Int. J. Marit. Eng. Vol 160, A-411-A-421. https://doi.org/10.3940/rina.ijme.2018.a4.505

Xu H, Guedes Soares C (2020) Vector field guidance law for curved path following of an underactuated autonomous ship model. Int. J. Marit. Eng. 162. https://doi.org/10.5750/IJME.V162IA3.1135

Xu H, Hinostroza MA, Guedes Soares C (2018) Estimation of hydrodynamic coefficients of a nonlinear manoeuvring mathematical model with free-running ship model tests. Int. J. Marit. Eng. Vol 160, A-213-A-226. https://doi.org/10.3940/rina.ijme.a3.2018.448

Xu H, Hinostroza MA, Guedes Soares C (2021a) Modified vector field path-following control system for an underactuated autonomous surface ship model in the presence of static obstacles. J. Mar. Sci. Eng. 9, 652. https://doi.org/10.3390/jmse9060652

Xu H, Hinostroza MA, Wang Z, Guedes Soares C (2020b) Experimental investigation of shallow water effect on vessel steering model using system identification method. Ocean Eng. 199, 106940. https://doi.org/10.1016/j.oceaneng.2020.106940

Xu H, Oliveira P, Guedes Soares C (2021b) L1 adaptive backstepping control for path-following of underactuated marine surface ships. Eur. J. Control 58, 357-372. https://doi.org/10.1016/j.ejcon.2020.08.003

Xu H, Rong H, Guedes Soares C (2019) Use of AIS data for guidance and control of path-following autonomous vessels. Ocean Eng. 194, 106635. https://doi.org/10.1016/j.oceaneng.2019.106635

Yamasaki T, Enomoto K, Takano H, Baba Y, Balakrishnan SN (2009) Advanced pure pursuit guidance via sliding mode approach for chase UAV. AIAA Guid. Navig. Control Conf. Exhib. https://doi.org/10.2514/6.2009-6298

Yanushevsky R (2011) Guidance of unmanned aerial vehicles. Taylor & Francis

Yu Y, Guo C, Yu H (2018) Finite-time predictor line-of-sight-based adaptive neural network path following for unmanned surface vessels with unknown dynamics and input saturation. Int. J. Adv. Robot. Syst. 15, 172988141881469. https://doi. org/10.1177/1729881418814699

Zhang G, Han J, Li J, Zhang X (2022) APF-based intelligent navigation approach for USV in presence of mixed potential directions: Guidance and control design. Ocean Eng. 260, 111972. https://doi.org/10.1016/J.OCEANENG.2022.111972

Zhang H, Zhang X, Bu R (2022) Sliding mode adaptive control for ship path following with sideslip angle observer. Ocean Eng. 251, 111106. https://doi.org/10.1016/J.OCEANENG.2022.111106

Zhang Z, Zhao Yuhan, Zhao G, Wang H, Zhao Yi (2021) Path-following control method for surface ships based on a new guidance algorithm. J. Mar. Sci. Eng. 2021, 9(2): 166. https://doi.org/10.3390/JMSE9020166

Zhu M, Sun W, Hahn A, Wen Y, Xiao C, Tao W (2020) Adaptive modeling of maritime autonomous surface ships with uncertainty using a weighted LS-SVR robust to outliers. Ocean Eng. 200, 107053. https://doi.org/10.1016/J.OCEANENG.2020.107053